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Growth and Productivity Dynamics of Proso Millet (*Panicum miliaceum* L.) under Water Stress at Pre- and Post-Flowering Stages

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This study investigated the response of proso millet (*Panicum miliaceum* L.) to water stress during its pre-flowering and post-flowering stages, aiming to inform sustainable agricultural practices and optimize water resource use under future climate challenges. This research was conducted during the 2024 growing season in the greenhouse, College of Agriculture, Samarra University, to study the effect of three different irrigation periods (4, 7, 14 days) on the growth and productivity of millet (Proso) during the pre- and post-flowering stages. A randomized complete block design with four replications was used. Results confirmed that water shortages significantly impacted millet plants during both pre- and post-flowering stages. Extending the irrigation interval to 14 days consistently led to a significant decline across all evaluated traits, with the most pronounced declines observed in plant height (57.44%) and total dry weight (69.07%) for the pre-flowering stress group compared to the control treatment. Conversely, the post-flowering stress group showed the greatest reductions in panicle number per plant (77.71%), 1000-grain weight (50.43%), panicle length (52.08%), grain yield per plant (57.93%), and drought resistance index (58%), also relative to the control. These reductions indicate that irregular irrigation and prolonged drought negatively impact physiological performance and overall productivity. Water stress during the post-flowering growth phase was more effective in reducing growth and yield, confirming that this phase is sensitive to water shortages. Irrigation every four days also yielded the best results for all traits, indicating the importance of regular water availability to ensure healthy growth and high yield.
Keywords: Global warming, carbon emissions, food security, Poaceae, semi-arid region, fodder crops, stress tolerance, drought stress.

INTRODUCTION

Proso millet (*Panicum miliaceum* L.), which belongs to the Poaceae family, is one of the main important cereal crops grown in arid and semi-arid areas for food and fodder purposes, this is due to its resistance to biotic and abiotic stresses, high productivity in poor soils, wide adaptability to diverse climatic conditions, and resistance to pests and diseases compared to other cereal crops (Rajput et al., 2024; Patil et al., 2024). Additionally, it requires significantly less water than wheat, rice, or maize, and has a shorter maturation period, with some types can reach maturity within 60-90 days (Bhat et al., 2019; Naresh et al., 2023). Besides its high nutritional value and easy digestibility, Proso millet contains high levels of carbohydrates, fats, proteins, and calcium, and has soluble fiber, about 36% of total fiber. It also has a lower sugar content compared to other cereals, making it an ideal food for individuals with diabetes. Proso millet varieties exhibit a wide range of nutrient content in their grains: iron (41-73 mg. kg^{-1}), zinc (26-47 mg. kg^{-1}), calcium (91-241 mg. kg^{-1}), and protein (11-19%) (Vetriventhan & Upadhyaya, 2018; Patil et al., 2024). But for this type of millet, protein and vitamin B3 are the main components, which is why it is used as a healing food, especially after illness or childbirth (Samreen & Kahkashan, 2024).

Climate change, characterized by significant increases in carbon emissions leading to global warming, poses substantial global challenges. Among these challenges, the agriculture and food sectors face severe issues as plants encounter serious environmental threats due to ongoing climate change, which causes yield reductions in many crop plants (Naresh et al., 2023). Climate change and drought conditions will significantly jeopardize crop and food productivity, potentially leaving countries unable to cope with such negative impacts (Bhat et al., 2019; Naresh et al., 2023). This raises the question of what alternative crops can achieve higher yields under limited agricultural resources, especially

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in marginal lands. Can millet contribute to solving the global food crisis?

Millet can be a sustainable solution to these crises, it can play a leading role in efforts to achieve sustainable development, eradicate hunger, adapt to climate change, enhance biodiversity, and transform agrifood systems, replacing other cereals with millet can help mitigate the risks of production shocks since millet withstands harsh environmental conditions that some local crop varieties no longer endure, leading to minimal yields due to climate change issues (Naresh et al., 2023). Proso millet contains genetic material characterized by a wide diversity in most qualitative traits. Therefore, this genetic material can be used as a guide for breeding programs to improve desirable traits, as well as for the potential release of new millet varieties that are more adaptable to climate change and drought (Tiwari et al., 2022); (Khatun et al., 2023); (Tiwari et al., 2023). The results of this research could also help guide plant breeding programs toward developing varieties that are more resistant to water stress, enhancing crop resilience to rapidly changing climates. Millet is drought-resistant, adaptable to low-input growth, and capable of producing high grain yields even under drought and heat stress conditions, compared to other cereal crops, this reduces the amount of water required for irrigation (Pathak, 2023). Although millet is considered a plant that tolerates semi-arid and arid climates, drought stress leads to serious adverse effects on its morphological characteristics, redox metabolism, and antioxidant defense system. It also disrupts cellular and functional homeostasis by affecting the content of osmotic regulators like soluble sugars (e.g., starch and sucrose biosynthesis) and proline (Choudhury et al., 2022; Wang et al., 2023). Hassan (2022) mentioned that the two wheat varieties (Sham 6 and Adnaniya) were exposed to water stress led to a decrease in growth indicators, grain yield, and their content of nitrogen and phosphorus. Bakheit et al. (2021) demonstrated in their study of twenty millet genotypes under normal irrigation and water stress conditions that the average weight of 1000 grains was 9.87 grams under normal irrigation, while it was 6.24 grams under water stress conditions.

Despite extensive studies on water stress in millet, knowledge of critical irrigation periods for growth and productivity is limited. The importance of this research stems from its role in studying the impact of water stress on two critical stages of millet growth: the pre-flowering and post-flowering stages. Understanding the extent to which millet is affected by water stress at different growth stages helps improve irrigation strategies and enhance its productivity. Considering the increasing challenges of climate change and rising temperatures, this study becomes essential for developing sustainable agricultural practices that maintain food security and enhance water use efficiency.

This research aims to evaluate the effect of different irrigation intervals (4, 7, and 14 days) on the growth and productivity of millet plants, analyze the plant's sensitivity to water stress at two key stages (pre- and post-flowering), and identify the stage most affected by drought, which will help guide more efficient irrigation management strategies.

MATERIAL AND METHODS

To determine the effect of water stress on the growth and productivity of 'Proso' millet during the pre-flowering and post-flowering stages, a pot experiment was conducted in the greenhouse of the College of Agriculture, Samarra University during the 2024 growing season.

***Material preparation*:** Plastic pots (each pot considered an experimental unit) 33 cm high and 29 cm in diameter were used. A constant soil weight of 10 kg was added, and the soil was subjected to chemical and physical analysis (Table 1).

The experiment consisted of two treatments, the first for the pre-flowering growth stage (D1), where the water deficit treatment began 25 days after planting and continued until the flowering stage (flowering occurred 53 days after planting).

The second treatment for the post-flowering growth stage (D2): The water deficit treatment began 40 days after planting and continued until maturity (crop maturity 125 days after planting). The number of experimental units reached 24.

The seeds were planted on April 13, 2024, at a rate of 10 seeds in each pot, and they were thinned after 10 days of germination to 5 plants and fertilized with NPK compound fertilizer at a ratio of 8:8:8 (4 g per pot) added to all pots before planting. The experiment included three irrigation periods: control treatment 4 (I_1), 7 (I_2), and 14 (I_3) days.

The traits studied were plant height (cm), total dry weight per plant (g), number of panicles per plant, 1000 - grain weight (g), panicle length (cm), grain yield per plant (g.plant^{1-}), drought resistance index (DI), measured according to Lan (1998).

$$DI = Ysi \times (Ysi/Ypi)/ Ys$$

Ysi: Yield under stress conditions

Ypi: Yield under non-stress conditions

Ys: Mean of grain yield under stressed conditions.

Table 1. Soil analysis results

Property	the value
Clay (%)	30.08
Silt (%)	9.52
Sand (%)	60.40
pH	7.65
EC conductivity (ds.m^{-1})	2.32
Organic matter (%)	0.90
Available Nitrogen (%)	11.25
Available phosphorous (%)	14.40
Available magnesium (%)	15.96
Available potassium (%)	16.35
Available chlorine (%)	9.50

***Statistical analysis*:** Data was statistically analyzed using a randomized complete block design (RCBD) with four replicates, according to SPSS version 24. Coefficient means were compared using the least significant difference (LSD) test between the means of the coefficients at a 5% probability level.

RESULTS AND DISCUSSION

***Plant height*:** The results in Table (2) indicate the presence of significant variation and a clear effect of the spacing of irrigation periods on the height of millet plants, as the results in the table above showed a decrease in the average height of the plant directly with the increase in irrigation periods, and the lowest rate was (25.75 cm) at the irrigation period of (14) days, where the percentage of decrease reached (57.44%) for the pre-flowering stage compared to the control treatment, which had the highest height. This may be due to a decrease in the soil water content, which leads to a reduction in the rate of water absorption, which is considered one of the necessary factors for the division and elongation of plant cells, which negatively affects the height of the plant Shakir (2022). Or the reason may be that plant growth is mainly done by cell division and differentiation, but drought limits cell division and elongation, leading to poor growth, mainly due to loss of turgor. Water stress conditions lead to poor cell elongation, because of poor water flow from the xylem tissue to neighboring cells, thus affecting plant height. These results are consistent with Zabn and Alsajri (2022); Shakir (2022).

Table 2. Effect of irrigation intervals on plant height, total dry weight of plant, and Panicle number per plant of proso millet.

Irrigation Periods	Averages of traits					
	Plant height (cm)		Total dry weight (g plant^{-1})		Number of panicles plant^{-1}	
	D_1	D_2	D_1	D_2	D_1	D_2
I_1	60.50	60.75	32.75	33.00	3.75	3.50
I_2	41.75	59.58	20.08	24.73	2.75	1.75
I_3	25.75	57.93	10.13	15.15	1.70	0.78
LSD (0.05)	4.49		3.71		0.18	

(D_1): Stage before flowering, (D2): Post-flowering stage, LSD: the least significant difference test between the means of the coefficients at a 5% probability level.

From Figure (1), we note that water stress in the pre-flowering stage had a higher effect on plant height, because this stress worked to limit vegetative growth and thus reduced elongation, which led to shorter plants. The effect of water stress after flowering was relatively less, as the plant had reached most of its final height before the stress was applied.

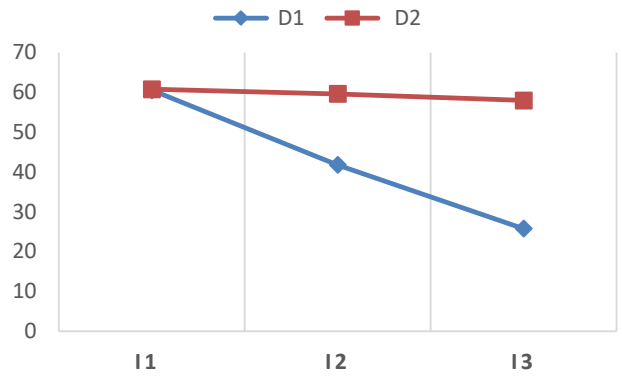

Figure 1. The effect of irrigation periods on plant height during the pre- and post-flowering stages. (D1): Stage before flowering, (D2): Post-flowering stage. (I1), (I2), (I3) Irrigation periods after 4, 7 and 14 days

***Total dry weight*:** From Table (2), we note a significant decrease in the dry weight of the millet plant due to its exposure to water stress when the irrigation periods are spaced out. The lowest rate (10.13 g. plant^{-1}) was reached for the irrigation treatment every 14 days for the pre-flowering stage, where the percentage of decrease was (69.07%). The highest percentage of decrease was reached (38.69%) for the irrigation treatment every 7 days for the same stage for the millet plant compared to the control treatment. The decrease in the total dry weight of the plant may be attributed to the decrease in plant height and the decrease in leaf area, which negatively affected the photosynthesis process and consequently decreased the total dry weight of the plant (Shakir, 2022). These results are consistent with Matsura & An (2020); Shakir (2022). From Figure (2), we note a greater decrease in the total dry weight of the plant compared to the pre-flowering stage, which led to fewer branches and a decrease in leaf area, which reduced photosynthesis and thus the total dry weight of millet.

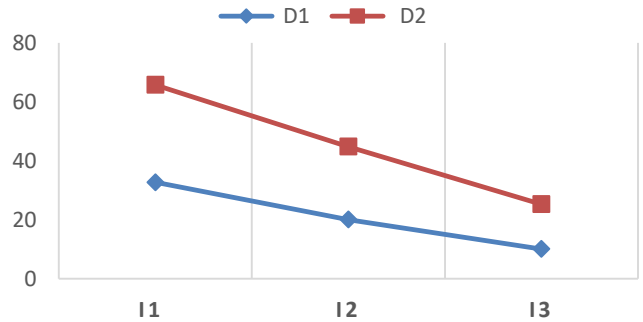

Figure 2. The effect of irrigation periods on total dry weight during the pre- and post-flowering stages. (D1): Stage before flowering, (D2): Post-flowering stage. (I1), (I2), (I3) Irrigation periods after 4, 7 and 14 days

***Number of panicles per plant*:** From the results of Table 2 and Figure 3, we note that there was a decrease in the number of panicles of millet plants exposed to water stress, but the effect was not significant compared to the flowering stage, as plants exposed to stress in the pre-flowering stage were able to restore part of their productive capacity when natural irrigation was resumed. The lowest rate of the number of spikes was (0.78) with a decrease rate of (77.71%) for the irrigation treatment every 14 days for the flowering stage. The reason may be that the lack of water affects the activity of cells in the growth area, which reduces the formation of new tissues, in addition to its effect on the absorption of minerals and essential elements, which reduces the plant's ability to form new panicles and thus reduces the number of panicles (Shakir, 2022). This is consistent with what Matsura and An (2020) found when they studied factors related to water and dry matter during the pre- and post-emergence period in four millet species under severe water shortage conditions.

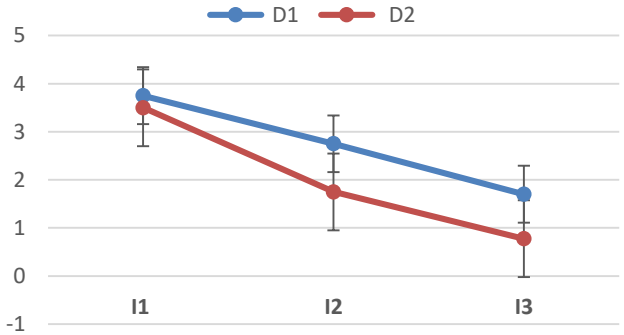

Figure 3. The effect of irrigation periods on number of panicles during the pre- and post-flowering stages. (D1): Stage before **flowering**, (D2): Post-flowering stage. (I1), (I2), (I3) Irrigation periods after 4, 7 and 14 days

***1000 - grain weight*:** The weight of 1000 - grains is considered one of the important factors that play a major role in determining the productivity of millet grains. Table 3 and Figure 4 showed that this trait was significantly affected by the irrigation periods for the pre- and post-flowering stages, but the effect of the trait in the flowering stage was greater compared to the pre-flowering stage, where the lowest rate (2.90 g) and the highest percentage of decrease (50.43%) was achieved for the 14-day irrigation period treatment in the post-flowering stage compared to the control treatment, which had the highest rate for this trait. This may be due to the increased rate of formation of small and deformed grains as a result of water stress, which is reflected in the weight of a thousand grains (Omran & Alloush, 2020). These results are consistent with Matsura and An (2020).

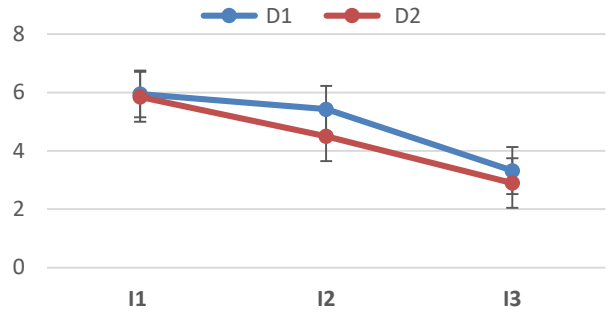

Figure 4. The effect of irrigation periods on 1000 - grain weight during the pre- and post-flowering stages. (D1): **Stage** before flowering, (D2): Post-flowering stage. (I1), (I2), (I3) Irrigation periods after 4, 7 and 14 days

***Panicle length*:** The length of the panicle is one of the factors affecting grain productivity. Table (3) and Figure (5) shows that the panicle length was clearly affected by the different irrigation periods. Plants exposed to water stress recorded a significant decrease in the pre- and post-flowering stages, but the decrease in panicle length in the post-flowering stage was greater, as the percentage of decrease reached (28.13%) and (52.08%) for the irrigation period of 7 and 14 days, respectively, compared to the control treatment. This may be because water stress reduces the plant's ability to absorb water from the soil, leading to a decrease in turgor pressure and thus reducing plant growth by reducing cell expansion. Drought also causes incomplete seed filling, which prevents proper seed development and reduces seed size (Nyaupane et al., 2024). limiting the longitudinal growth of the panicle. This is consistent with Bakheit et al. (2021) where they found that

Table 3. Effect of irrigation intervals on 1000-grain weight, panicle length, grain yield per plant and drought resistance index of proso millet.

Irrigation Periods	Averages of traits							
	- grain1000		Panicle length (cm)		Grain yield		Drought resistance index	
	D_1	D_2	D_1	D_2	D_1	D_2	D_1	D_2
I_1	5.95	5.85	24.50	24.00	25.13	25.08	1.00	1.00
I_2	5.43	4.50	20.50	17.25	21.55	19.25	0.86	0.77
I_3	3.33	2.90	14.75	11.50	13.60	10.55	0.56	0.42
LSD (0.05)	0.281		4.887		2.241		0.012	

(D_1): Stage before flowering, (D2): Post-flowering stage. LSD: the least significant difference test between the means of the coefficients at a 5% probability level.

irrigation treatments, genetic compositions and their interactions in millet plants had a significant impact on spike length for both seasons.

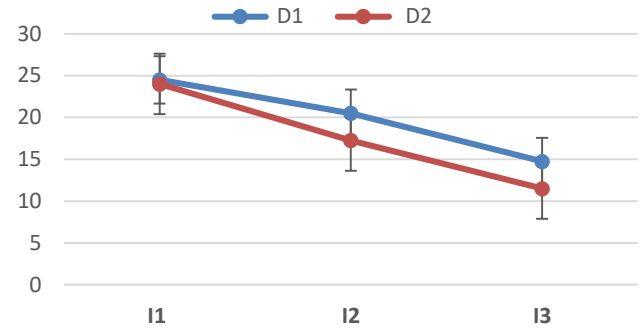

Figure 5. The effect of irrigation periods on Panicle length during the pre- and post-flowering stages. (D1): Stage before flowering, (D2): Post-**flowering** stage. (I1), (I2), (I3) Irrigation periods after 4, 7 and 14 days

***Grain yield*:** The results of Table (3) and Figure (6) showed a significant decrease in the yield of millet plants with the increase in the period of water stress, as plants irrigated every 14 days recorded the lowest yield (10.55 g. plant^{-1}) compared to plants irrigated every 4 and 7 days, and the highest percentage of decrease in grain yield (45.88% and 57.93%) was reached for the irrigation period every 14 days for the pre- and post-flowering stage respectively, compared to the control treatment, this confirms the severity of the impact of water stress in the post-flowering stage, compared to the pre-flowering stage, where plants showed an ability to partially compensate for the loss when irrigation conditions were subsequently improved. The reason for the reduced grain yield may be that the meiosis and sporogenesis stages of pollen development are highly sensitive to water stress, leading to pollen sterility and, consequently, poor fertilization and reduced grain production (Nyaupane et al., 2024). These results are consistent with those of Matsura and An (2020) when they studied the effect of water stress on four millet species.

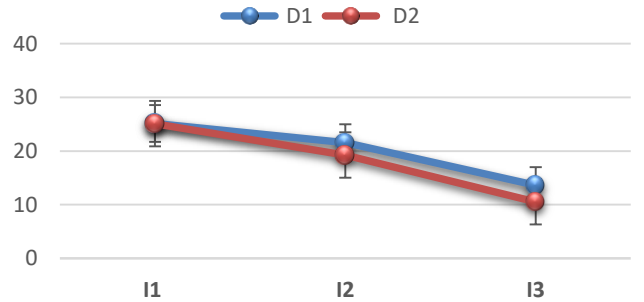

Figure 6. The effect of irrigation periods on grain yield during the pre- and post-flowering stages. (D1): Stage before flowering, (D2): Post-flowering stage. (I1), (I2), (I3) Irrigation periods after 4, 7 and 14 days

***Drought resistance index*:** Water deficiency is an important indicator of drought resistance, as it determines the plant's water status. It is defined as the ratio of the amount of water lost to fully saturated cells to their total content at full tissue saturation, expressed as a percentage. Water deficiency in plants occurs during the hot day and is fully or partially replenished at night. In other words, the remaining water deficiency indicates an imbalance between water intake and utilization (Viktorovych et al., 2023). The drought tolerance index (DTI) varied significantly (Table 3 and Figure 7), with the DTI being less than one for the 7 and 14-day irrigation periods. The decline in DTI was greatest in the post-flowering stage, reaching 0.77 and 0.42, respectively, with a 23% and 58% decrease for the 7 and 14-day irrigation periods, respectively. These results are consistent with those of Bakheit et al. (2021), who studied the impact of water stress on four millet varieties and twenty millet genotypes during the 2019 and 2020 seasons

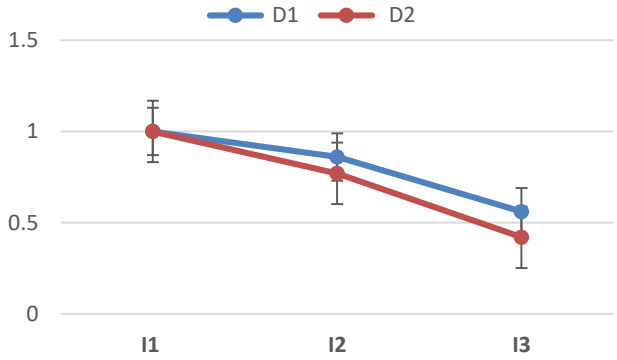

Figure 7. The effect of irrigation periods on drought resistance index during the pre- and post-flowering. (D1): Stage before flowering, (D2): Post-flowering stage. (I1), (I2), (I3) Irrigation stages periods after 4, 7 and 14 days

***Conclusion*:** This research highlights the importance of Proso millet as a sustainable agricultural solution to address the challenges of climate change and desertification, particularly in arid and semi-arid regions. It also contributes to understanding the impact of moisture stress on the growth and production of this plant, both pre- and post-flowering. Based on the research results, it can be concluded that increasing the irrigation interval leads to a clear decrease in all studied traits of the millet plant, especially when exposed to water stress before the flowering stage. That is, the timing of water stress has a negative impact on millet growth and productivity, especially during the pre-flowering stage. This suggests that the early stages of growth, especially pre-flowering, are most sensitive to water shortages. Therefore, to ensure high productivity, it is important to avoid exposing millet to water stress during this critical stage, with an emphasis on providing adequate irrigation before flowering.

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***SDGs addressed*:** No poverty; Zero hunger; good health and well-being.

***Policy referred*:** National Climate Change Adaptation Strategy; National Water Policy.

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